

APPENDIX C

Amplification Discussion

C-1. General.

a. Features such as powerhouse walls, parapets, and other appendages that project away from larger supporting substructures are subject to amplification. A powerhouse substructure is a high-frequency responder that acts as a filter attenuating low-frequency motions but amplifying the seismic motion near the substructure's own natural frequency. With respect to powerhouse superstructure walls, amplification effects will be automatically picked up when composite substructure-superstructure analytical models are used for the seismic evaluation. However, when the superstructure is decoupled from the substructure (superstructure-only models), any influence amplification has on total earthquake demand will be missed. The maximum amplification occurs when the period of the substructure (T_I) or (T_I') nears the period of one of the principal modes of vibration for the superstructure (T). Principal modes of vibration that are of interest are illustrated in Figure B-4. Resonance can also occur at the superstructure's higher modes of vibration. Although these higher-frequency modes can magnify force demands, they have little effect on displacement demands. The amplified force demands associated with these higher modes of vibration can cause shear demands to increase significantly. However, it must be recognized that shear demand is limited and need not exceed a demand corresponding to 1.5 times that of the member's nominal moment capacity.

b. It has long been recognized that displacements are the best indicator of structure performance and damage. Therefore, since higher-mode displacement demands are low and shear demand is limited, it is only necessary when assessing displacement ductility demand to consider those amplification effects associated with the low-frequency modes of the superstructure. Evaluators wishing to investigate the impact that higher-frequency modes of vibration may have on displacement demand are referred to Qi and Moehle (1991).

c. Powerhouse superstructures are generally short-period systems with a fundamental period less than the characteristic ground motion period (i.e., intersection of the constant acceleration response and constant velocity response regions). Response is usually in the constant acceleration range of the response spectrum (Figure C-1a)

d. This means that the earthquake demand on the substructure will be at a maximum and the spectral acceleration will be equal to 2.5 times the peak ground acceleration (PGA). Amplification will increase the demand on superstructure walls (assuming linear elastic behavior) by about six, meaning that the demands on the superstructure could reach 6×2.5 , or about 15 times the PGA. This amplification applies to those generator bay composite models and erection/service bay block models as described in Ebeling, Perez-Marcial, and Yule (2006). The erection bay/service bay block-frame model described in Ebeling, Perez-Marcial, and Yule (2006) is a hybrid system considered to be best evaluated using composite modeling techniques. This particular system will therefore not be addressed with respect to a superstructure-only analysis.

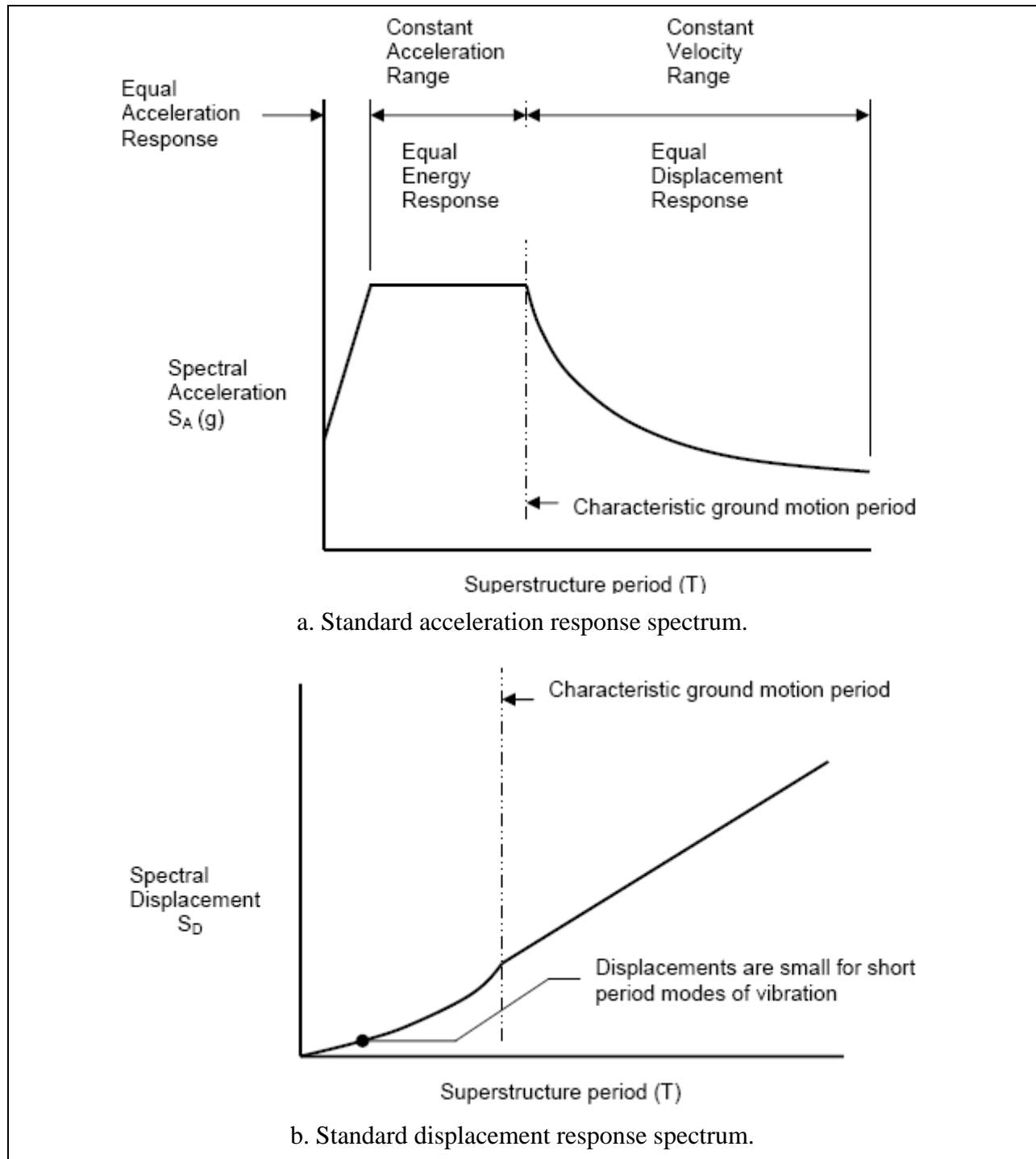


Figure C-1. Top-of-rock response spectra.

e. Amplification occurs due to height-wise acceleration occurring in the substructure and to resonance amplification occurring when the period of the superstructure nears that of the substructure. The intent of Appendix C is to:

- Describe height-wise amplification effects with respect to powerhouse substructures.
- Use data from Ebeling, Perez-Marcial, and Yule (2006) to develop simple methods that can be used to estimate the period of the substructure.
- Use data from Ebeling, Perez-Marcial, and Yule (2006) and NCEER-93-0003 to develop a simple method for estimating resonance amplification effects in superstructure-only models.
- Use data from Ebeling, Perez-Marcial, and Yule (2006) to provide guidance for determining when a superstructure will experience negligible amplification.
- Discuss the amplification provisions contained in FEMA 356 (2000) with respect to parapets and appendages.
- Suggest an alternative time-history approach for estimating amplification effects.

C-2. Discussion of Ebeling, Perez-Marcial, and Yule (2006).

a. A typical relationship between amplification and frequency per the Ebeling, Perez-Marcial, and Yule (2006) report is illustrated in Figure C-2.

b. The powerhouse substructure is a high-frequency (short-period) responder. It acts as a filter amplifying the high-frequency motion near the substructure's own natural frequency and somewhat attenuates (reduces) lower-frequency motions. The peak amplification response will occur when the substructure and superstructure have identical periods of vibration.

c. Relationships between amplification and frequency obtained from the Ebeling, Perez-Marcial, and Yule (2006) report will be used to:

- Develop simple formulas that can be used to estimate the substructure's fundamental period for generator bay block models and erection/service bay block models under both "dry" and "wet" conditions. The substructure's fundamental period for the "dry" condition is designated as T_I and for the "wet" condition as T_I^I .
- Determine the peak resonance amplification (a_p) as a function of the substructure's fundamental period of vibration (T_I). Total amplification (AF) divided by the height-wise amplification (a_x) equals the peak resonance amplification (a_p).
- Determine the superstructure-to-substructure period ratio (T/T_I) or (T/T_I^I) where amplification is negligible (need not be considered).

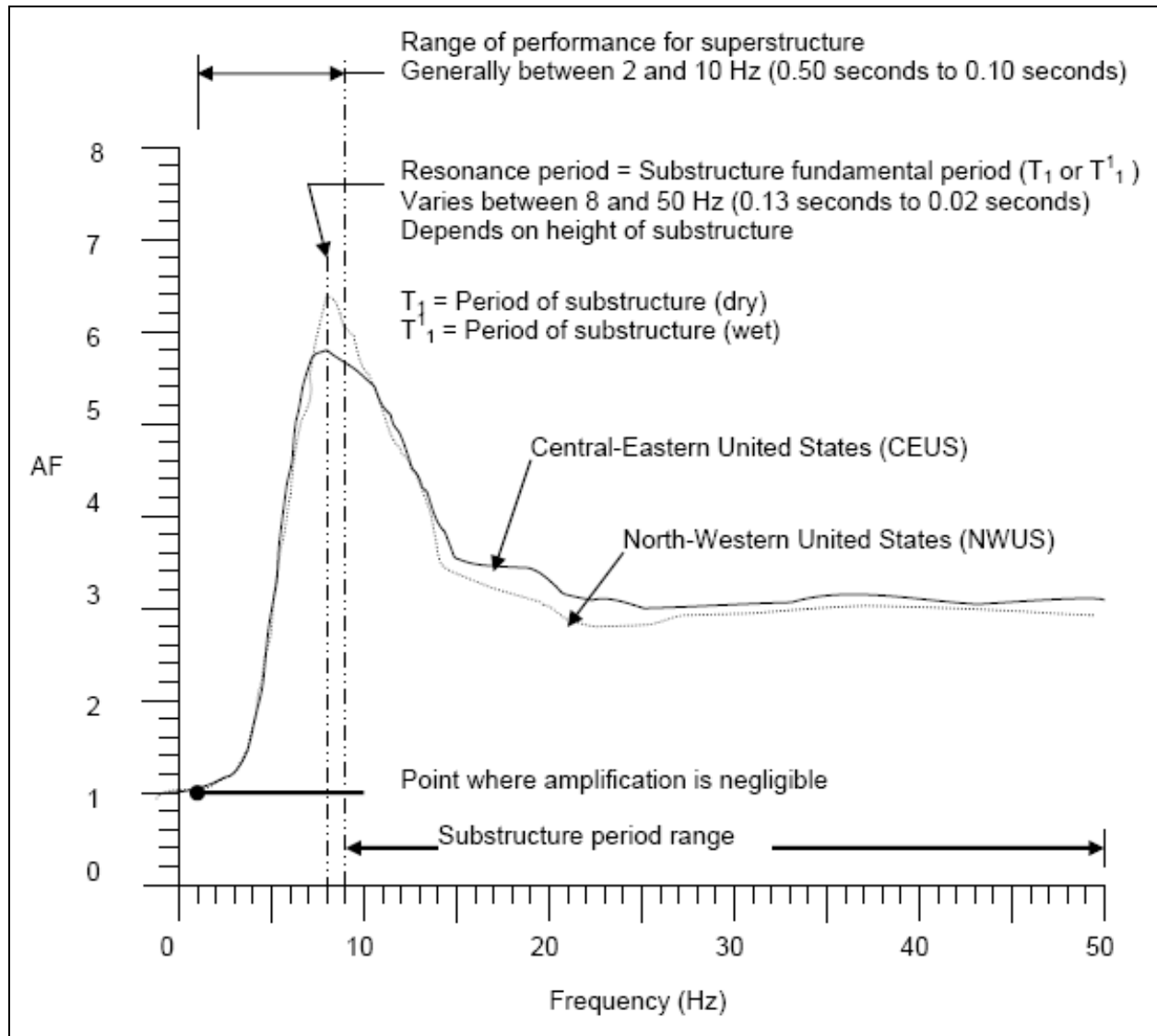


Figure C-2. Typical amplification plot from Ebeling, Perez-Marcial, and Yule (2006). AF is the amplification factor, which is the acceleration of SDOF on top of substructure divided by the acceleration of SDOF on top of rock, or the height-wise amplification (a_x) multiplied by the resonance amplification (a_p).

d. The figures contained in Section 5.2, "Recommended Amplification Factor Relationships for Generator Bay Composite Models," and Section 5.3, "Recommended Amplification Factor Relationships for Erection / Service Bay Block Models," of Ebeling, Perez-Marcial, and Yule (2006) are used to accomplish the above objectives. Information from the Ebeling, Perez-Marcial and Yule (2006) Section 5.2 and 5.3 figures important to this effort is presented in Tables C-1 through C-8.

Table C-1. Generator bay composite model (dry).

Substructure Height (ft)	Resonance		AF @ Resonance	
	F (Hz)	T ₁ (s)	NWUS	CEUS
125	10	0.100	6.6	5.8
100	13	0.077	7.1	6.8
75	20	0.050	3.8	6.5
40	33	0.031	1.0	3.3

Table C-2. Generator bay composite model (wet).

Substructure Height (ft)	Resonance		AF @ Resonance	
	F (Hz)	T ₁ (s)	NWUS	CEUS
125	7.5	0.130	6.0	7.2
100	10.5	0.095	5.8	4.8
75	15.0	0.067	4.8	6.2
40	25.0	0.040	2.4	4.8

Table C-3. Erection / service bay block model (dry).

Substructure Height (ft)	Resonance		AF @ Resonance	
	F (Hz)	T ₁ (s)	NWUS	CEUS
110	11.0	0.091	6.0	5.7
75	17.5	0.057	4.4	6.0
45	33.0	0.030	1.0	5.0
20	-----		1.0	1.0

Table C-4. Erection / service bay block model (wet).

Substructure Height (ft)	Resonance		AF @ Resonance	
	F (Hz)	T ₁ (s)	NWUS	CEUS
110	8.5	0.118	7.0	6.8
75	15.0	0.067	5.1	6.2
45	25.0	0.040	1.5	3.5
20	-----		1.0	1.0

Table C-5. Generator bay composite model (dry) for substructure period (T₁) and superstructure period (T) where AF = 1.

Substructure Height (ft)	T ₁ (s)	At AF = 1		T / T ₁
		F (Hz)	T (s)	
125	0.100	3.0	0.33	3.3
100	0.077	5.0	0.26	2.6
75	0.050	7.5	0.13	2.6
40	0.031	15.0	0.07	2.3

Table C-6. Generator bay composite model (wet) for substructure period (T_1) and superstructure period (T) where $AF = 1$.

Substructure Height (ft)	T_1 (s)	At $AF = 1$		T / T_1
		F (Hz)	T (s)	
125	0.130	2.0	0.500	3.8
100	0.095	4.0	0.250	2.6
75	0.067	6.0	0.170	2.5
40	0.040	10.0	0.100	2.5

Table C-7. Erection / service bay block model (dry) for substructure period (T_1) and superstructure period (T) where $AF = 1$.

Substructure Height (ft)	T_1 (s)	At $AF = 1$		T / T_1
		F (Hz)	T (s)	
110	0.091	3.0	0.330	3.6
75	0.057	5.0	0.200	3.5
45	0.030	18.0	0.060	2.0
20	-----			

Table C-8. Erection / service bay block model (wet) for substructure period (T_1) and superstructure period (T) where $AF = 1$.

Substructure Height (ft)	T_1 (s)	At $AF = 1$		T / T_1
		F (Hz)	T (s)	
110	0.118	3.0	0.330	2.8
75	0.067	5.0	0.200	3.0
45	0.040	18.0	0.060	1.5
20	-----			

e. Simple formulas that can be used to estimate the substructure's fundamental period for generator bay block models and erection/service bay block models under both "dry" and "wet" conditions are developed based on the data contained in Tables C-1 through C-4. Plots of these data along with a plot of a linear equation that best fits the data are provided in Figures C-3 through C-6.

f. Peak resonance amplification (a_p) in the superstructure occurs at the substructure's fundamental period of vibration (T_1 or T_1^I). The total amplification (AF) divided by the height-wise amplification (a_x) equals the peak resonance amplification (a_p). The height-wise amplification (a_x) is assumed to be 1.2 based on information presented in Section C-3.

g. It is generally accepted that if the period of an appendage (in this case the powerhouse superstructure) is less than 0.06 seconds, then no dynamic amplification is expected. Therefore, only those AF values corresponding to substructures with periods of 0.06 seconds or greater will be used to estimate a reasonable AF for use in the assessment of superstructure-only models. The information in Tables C-1 through C-4 for substructures with periods greater than 0.06 seconds shows that a total amplification equal to 6.0 is reasonable.

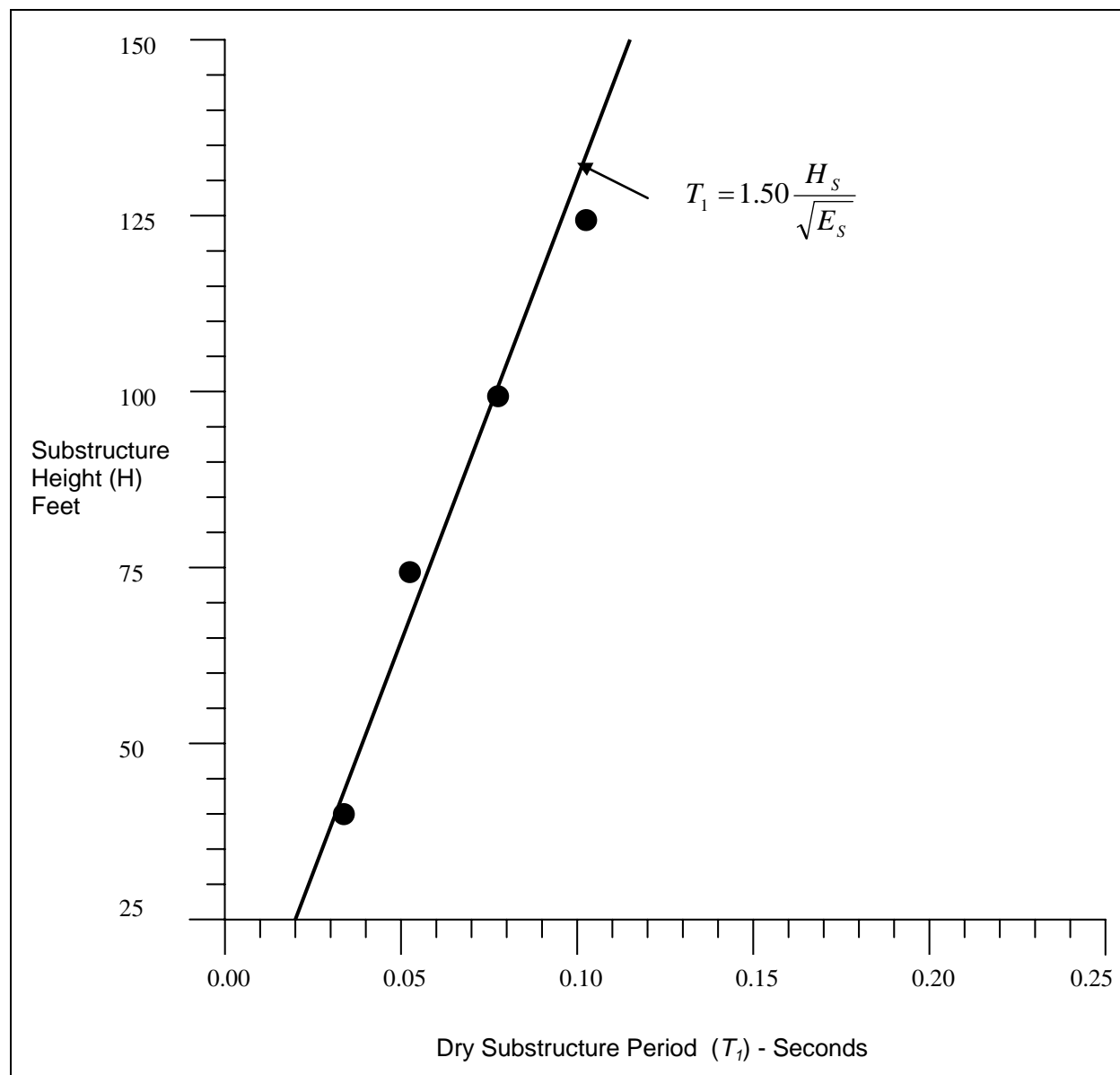
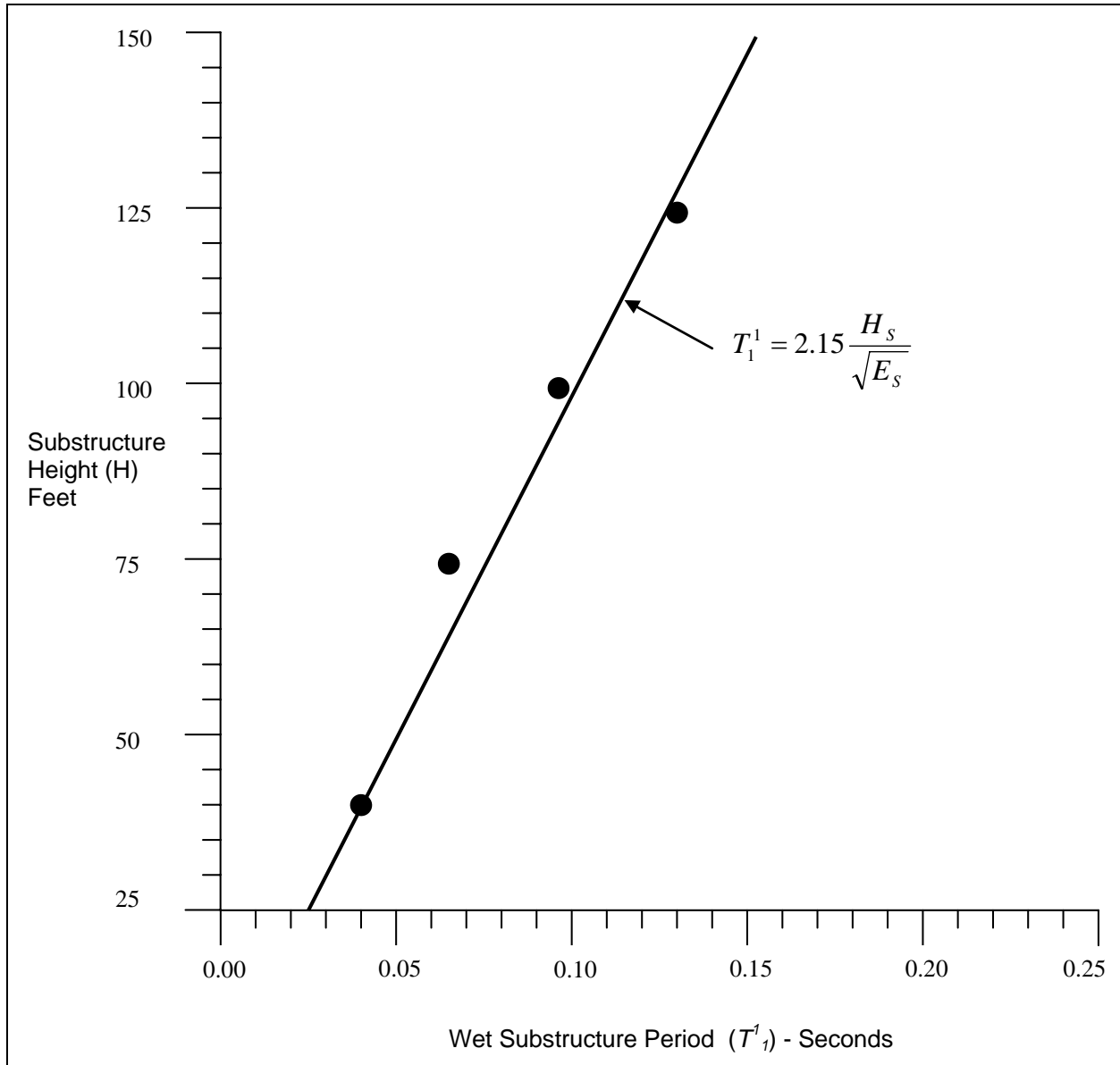


Figure C-3. Generator bay block model (dry).

31 Oct 06

**Figure C-4. Generator bay block model (wet).**

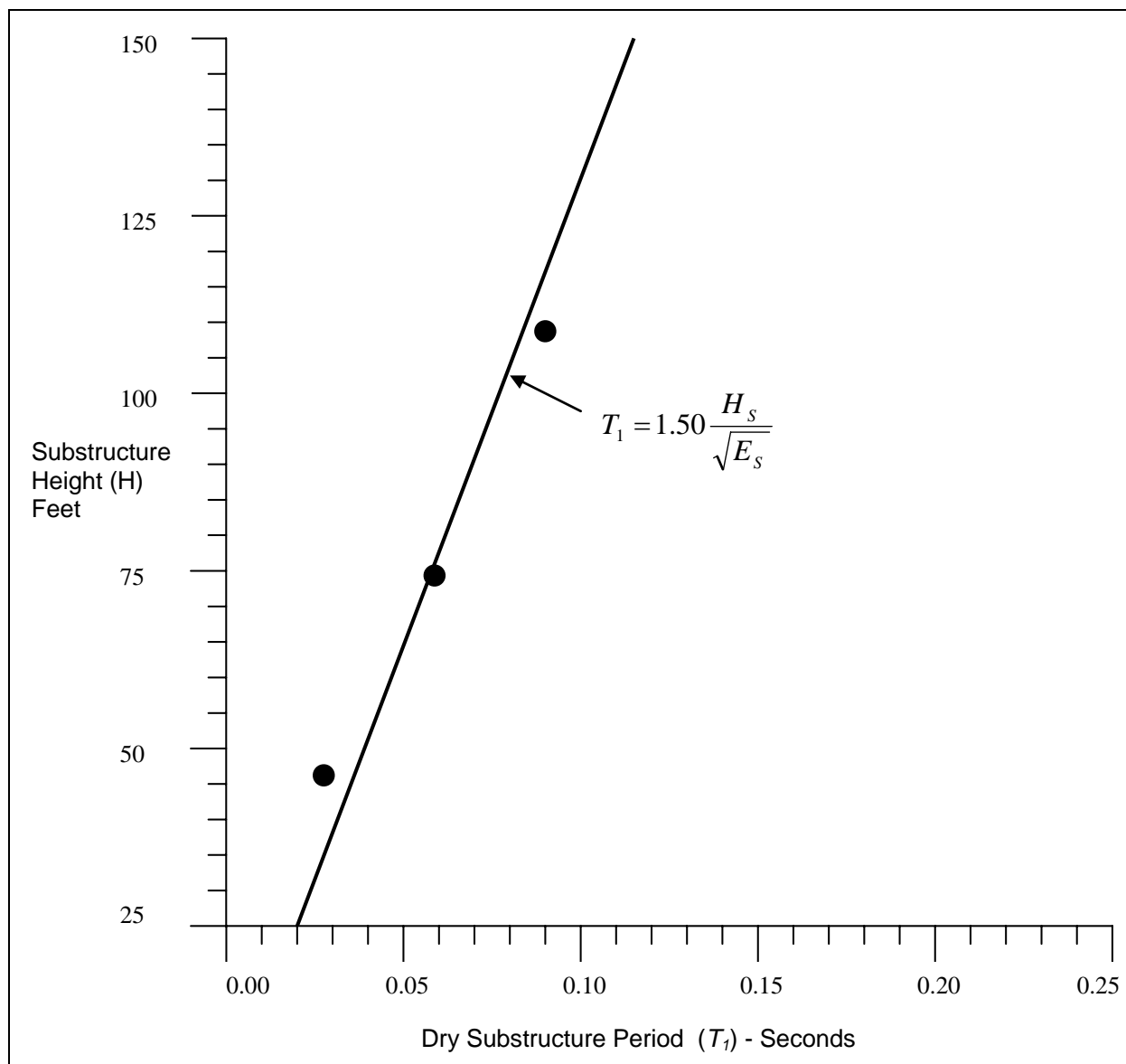


Figure C-5. Erection bay block model (dry).

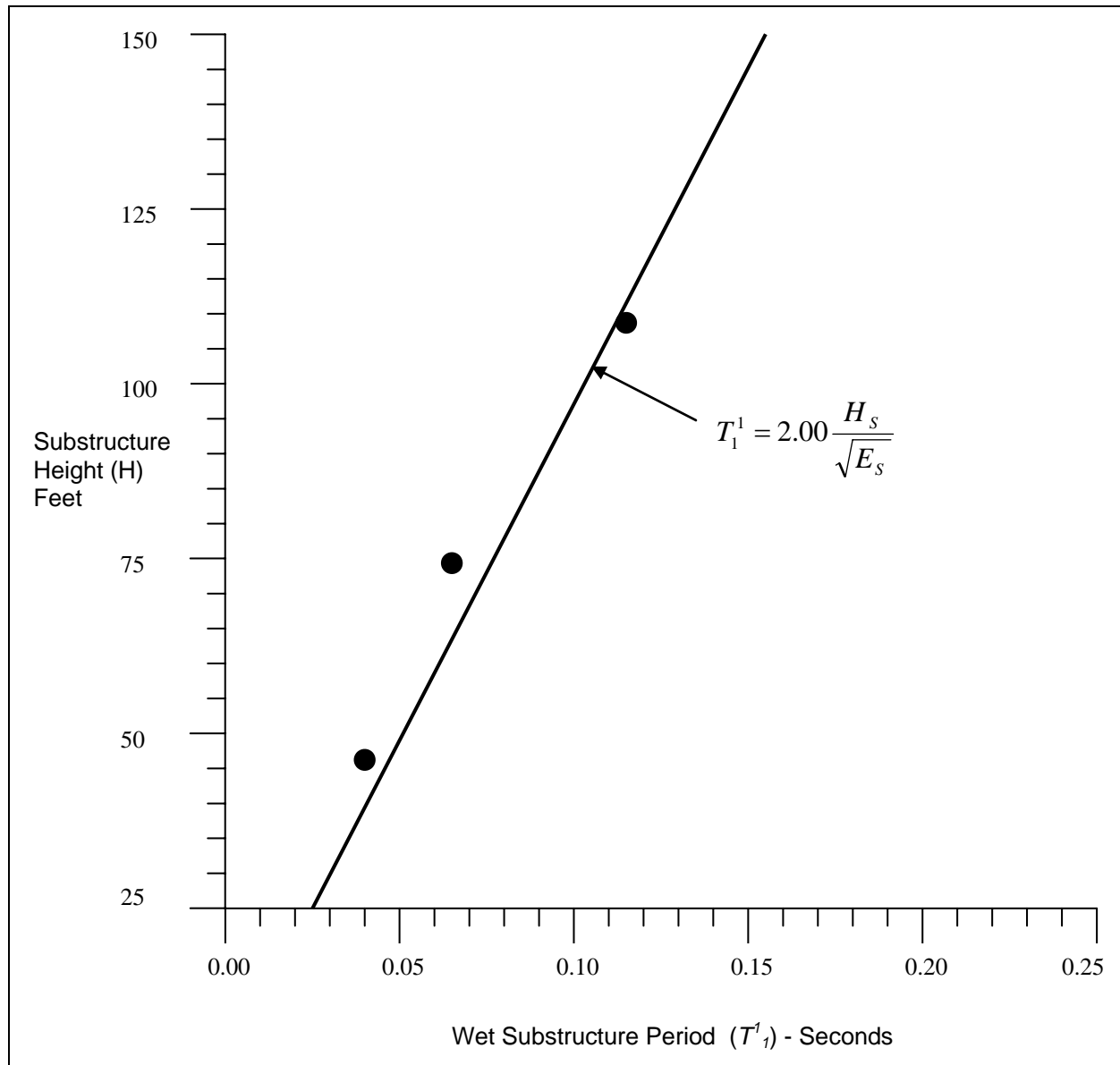


Figure C-6. Erection bay block model (wet).

h. Tables C-5 through C-8 are used to determine the superstructure-period-to-substructure-period ratio (T/T_1) or (T/T_1^1) where amplification of the superstructure is negligible and need not be considered. This occurs because low-frequency attenuation effects cancel out height-wise amplification effects. Again, using only those total AF values corresponding to substructures with periods of 0.06 seconds or greater, it can be seen that a superstructure-period-to-substructure-period ratio of 3.0 would be a reasonable point to assume the effects of amplification will be negligible. This can be confirmed by reviewing the amplification plots contained in Section 5 of Ebeling, Perez-Marcial, and Yule (2006).

C-3. Height-Wise Amplification.

a. Height-wise amplification occurs in powerhouse substructures because the center of seismic force is below the top of the substructure, the location where the superstructure rests. The effective height (l_{eff}) representing the center of seismic force is:

$$l_{eff} = \frac{\sum (m_n \phi_n l_n)}{\sum m_n \phi_n} \quad (C-1)$$

where:

m_n = mass at level n of a multiple lumped mass system

l_n = height from base to mass at level n

ϕ_n = modal value at mass level n .

b. The center of seismic force (l_{eff}) is illustrating for a powerhouse substructure with uniform mass and stiffness with a linear first mode shape (Figure C-7).

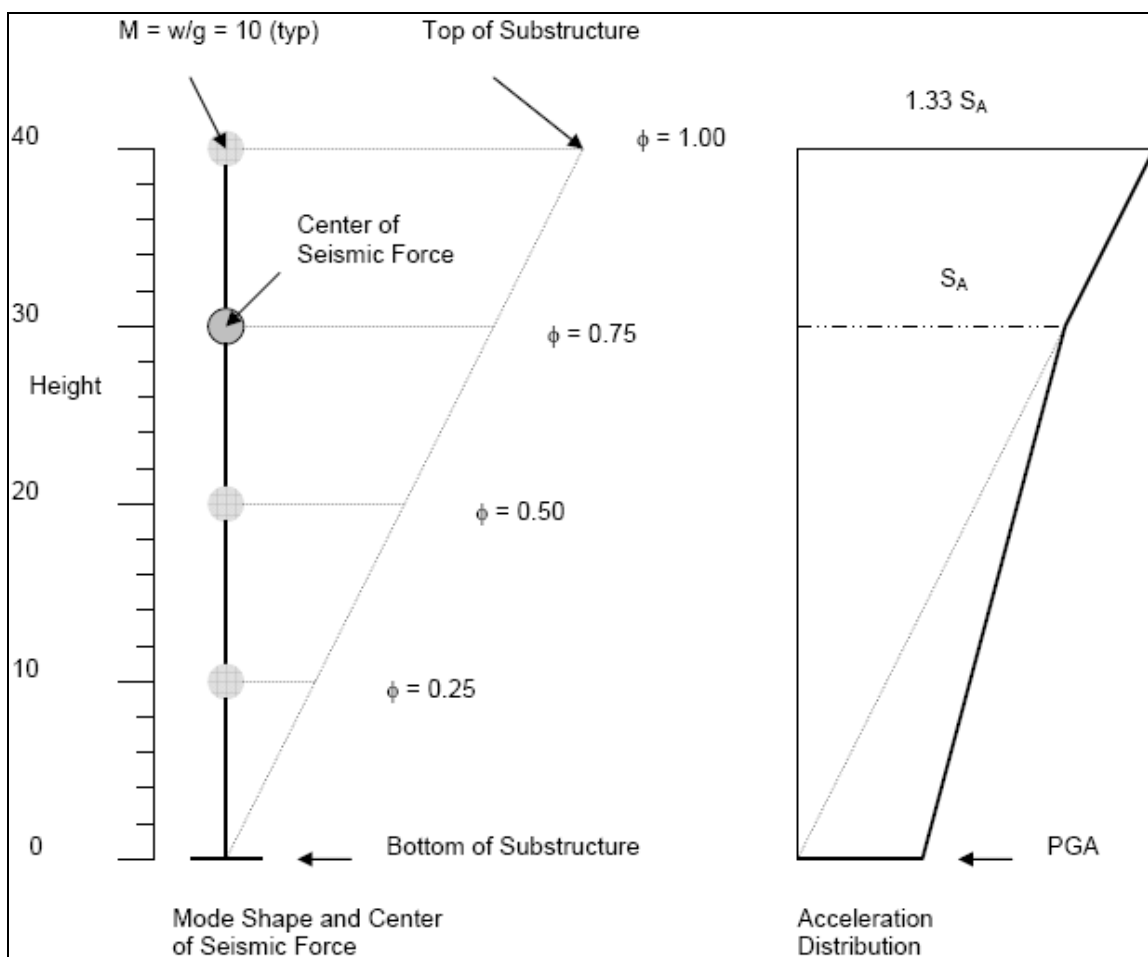


Figure C-7. Center of seismic force effects for linear mode shape.

c. Calculation of the center of seismic force is as follows:

$$l_{eff} = \frac{\sum (m_n \phi_n l_n)}{\sum m_n \phi_n} = \frac{10(1.00)40 + 10(0.75)30 + 10(0.50)20 + 10(0.25)(10)}{10(1.00) + 10(0.75) + 10(0.50) + 10(0.25)} \\ = \frac{750}{25} = 30 \text{ ft.}$$

d. Since the acceleration at the center of seismic force equals the spectral acceleration (S_A), the acceleration at the top of the substructure (A_T) is equal to:

$$A_T = \frac{1.00}{0.75} S_A = 1.33 S_A. \quad (\text{C-2})$$

e. Also, the acceleration at the top of the substructure (A_T) is equal to:

$$A_T = PF(S_A)$$

where PF is the modal participation factor.

f. Calculations for the modal participation factor are as follows:

$$PF = \frac{\sum m \phi}{\sum m \phi^2} = \frac{10 + 7.5 + 5.0 + 2.5}{10 + 5.625 + 2.5 + 0.625} = \frac{25}{18.75} = 1.33.$$

g. Therefore, $A_T = 1.33 S_A$.

h. Acceleration at the top of the substructure can be determined either by a center of seismic force approach or a modal participation factor approach. The Ebeling, Perez-Marcial, and Yule (2006) study indicates that shear displacement governs the substructure's first mode response, assuming a mode shape approximating that for shear displacement as illustrated in Figure C-8.

i. Calculation of the center of seismic force is as follows:

$$l_{eff} = \frac{\sum (m_n \phi_n l_n)}{\sum m_n \phi_n} = \frac{10(1.00)40 + 10(0.90)30 + 10(0.50)20 + 10(0.10)(10)}{10(1.00) + 10(0.90) + 10(0.50) + 10(0.10)} \\ = \frac{780}{25} = 31.2 \text{ ft.}$$

j. Calculations for the modal participation factor (PF) are as follows:

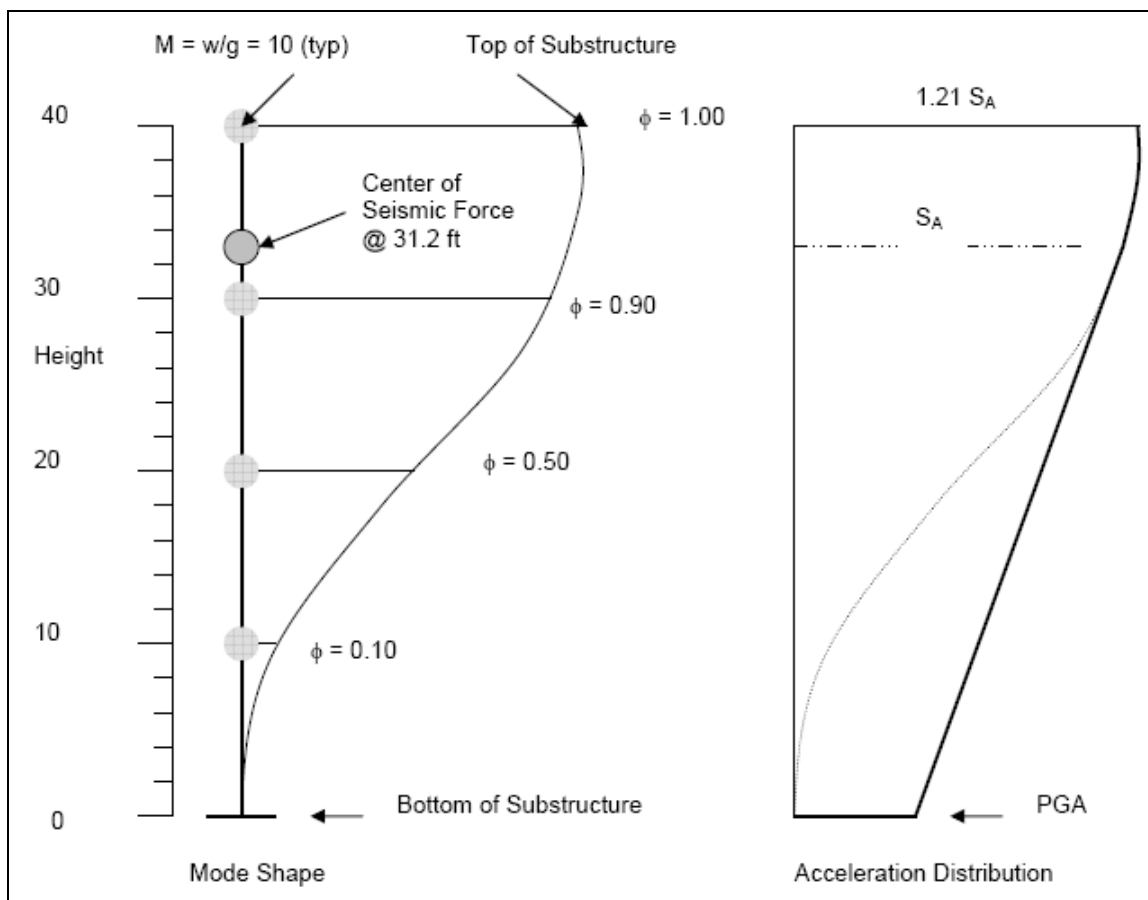


Figure C-8. Center of seismic force for shear displacement response.

$$PF = \frac{\sum m\phi}{\sum m\phi^2} = \frac{10 + 9.0 + 5.0 + 1.0}{10 + 8.1 + 2.5 + 0.1} = \frac{25}{20.7} = 1.2.$$

k. The acceleration at the top of the substructure (A_T) is equal to:

$$A_T = PF(S_A) = 1.2S_A.$$

l. Height-wise amplification occurring in powerhouse superstructures can be based on the following assumptions:

- The substructure and superstructure will respond in the acceleration-sensitive range of the response spectra.
- Only first mode effects need be considered.
- The first mode participation factor (PF) is equal to 1.2.

m. Height-wise amplification (a_x) of acceleration if both the substructure and superstructure appendages are responding in the constant acceleration range is equal to 1.2. In other words, the acceleration the superstructure appendage will experience is 1.2 times that it would experience if it were founded on top of rock. With the spectral acceleration in the constant acceleration range equal to 2.5 times the peak ground acceleration (PGA), the force the superstructure appendage will experience due to height-wise acceleration is equal to 1.2×2.5 , or 3.0 times the PGA.

C-4. Resonance-Related Amplification. Resonance-related amplification takes place as the period of the superstructure approaches that of the substructure. The total amplification for substructures of various heights is presented above in Section C-2. With respect to generator bay substructures and erection/service bay block substructures responding in the constant-acceleration range, the maximum total amplification is approximately equal to six. Assuming that the height-wise amplification effect is equal to 1.2, the peak amplification attributable to resonance is equal to $6.0 \div 1.2$, or 5.0. The range of the peak resonance response should be broadened from that indicated in the Ebeling, Perez-Marcial, and Yule (2006) report to account for inaccuracies in the determination of the substructure period (T_I) or (T_I') and the superstructure period (T). In this respect, the recommendations presented in National Center for Earthquake Engineering Research Technical Report NCEER-93-003 will be followed. The substructure-period-to-superstructure-period ratio (T/T_I) is used to define the region where peak resonance occurs. Following NCEER-93-003 recommendations, the range of peak response is broadened from 0.7 (T/T_I) to 1.4 (T/T_I). Also, according to the NCEER study, resonance amplification effects outside the range of 0.5 (T/T_I) to 2.0 (T/T_I) are considered to be negligible. Based on the above discussion, the application of resonance response amplification for superstructure-only models can be in accordance with Figure C-9.

C-5. Amplification Provisions Contained in FEMA 356 (2000).

a. The provisions in FEMA 356 (2000) relating to parapets and appendages are examined to understand how they might compare with the provisions in Sections C-3 and C-4 above proposed for height-wise and resonance amplification of powerhouse superstructures. FEMA 356 (2000) contains general equation for amplification and an equation that establishes a default limit on amplification. The amplification suggested by Figure C-9 is higher than that which would occur using the general equation and much higher than that using the default limit.

b. From the FEMA 356 (2000) general equation:

$$F_p = \frac{0.4a_p S_s I_p W_p}{R_p} \left[1 + 2 \frac{x}{h} \right] \quad (\text{C-3a})$$

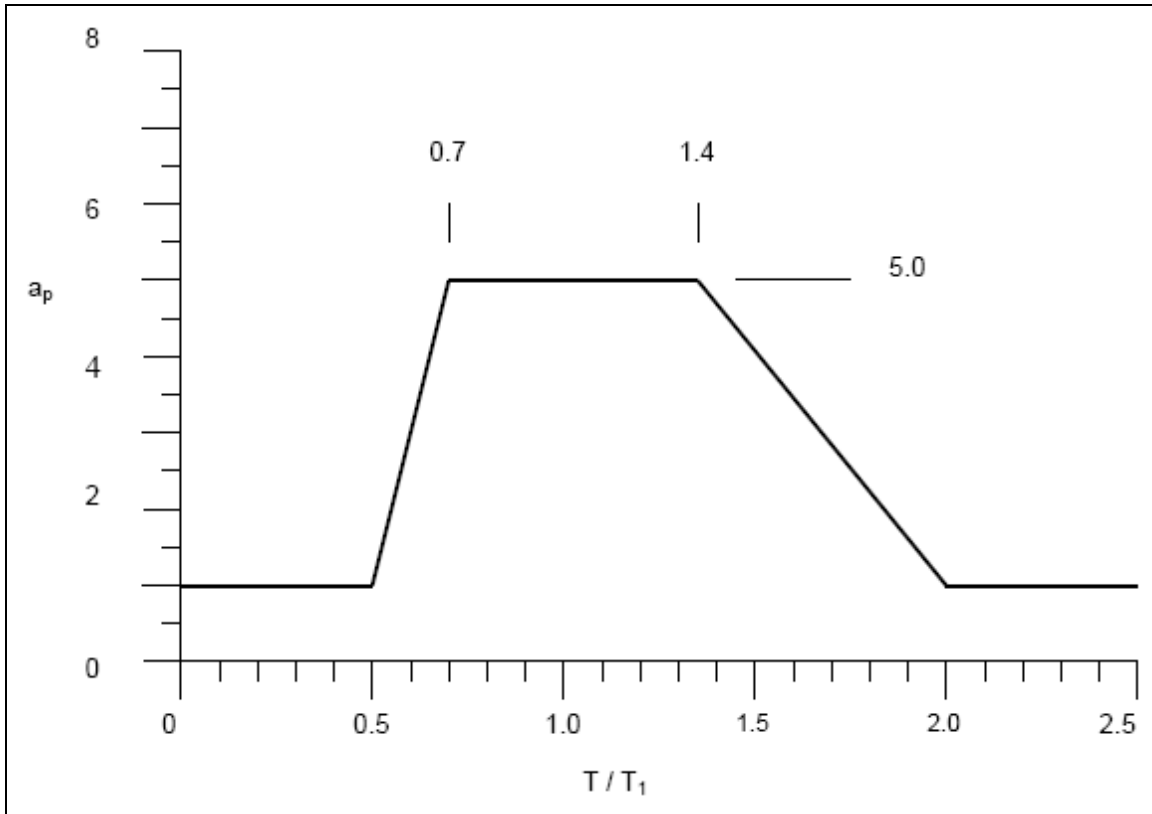


Figure C-9. Resonance effects amplification: resonance amplification factor (a_p) versus period ratio (T / T_1) with a constant acceleration response.

where:

F_P = horizontal seismic force on component or equipment

a_p = amplification factor (equal to 2.5 for parapets and appendages)

S_S = spectral acceleration for the constant acceleration range of the response spectrum

W_P = weight of the parapet or appendage

R_P = response modification factor (assume to be 1.0 for powerhouse DCR evaluations)

I_P = importance factor (assume to be 1.0 for powerhouse performance evaluations)

x = elevation in substructure relative to its base

h = height of substructure relative to its base.

c. Since the interest here is in the acceleration at the top of the substructure, elevation x is set equal to h , the height of the substructure. Also, by setting:

$$a_p = 2.5$$

$$R_P = 1.0$$

$$I_P = 1.0,$$

Equation C-3a becomes:

$$F_p = 3.0S_s W_p, \quad (C-3b)$$

indicating that the acceleration at the top of the substructure is equal to 3 times the top-of-rock spectral acceleration and, since performance is the constant-acceleration range, equal to 7.5 times the peak ground acceleration (i.e., 7.5 PGA).

d. This is half the product of the height-wise amplification and resonance amplification ($1.2 \times 5.0 \times 2.5 = 15$ PGA) proposed for powerhouse superstructures as described in Sections B-2 and B-3 above.

e. The FEMA 356 (2000) provisions limit the maximum force on components to:

$$F_p = 1.6S_s I_p W_p. \quad (C-4)$$

f. Recognizing that $0.4 (S_{DX})$ equals the peak ground acceleration for the design earthquake and taking I_p equal to one, the above formulation can be rewritten to:

$$F_p = 4.0(PGA)W_p. \quad (C-5)$$

g. This is about one-quarter the product of the height-wise amplification and resonance amplification proposed for powerhouse superstructures as described in Sections C-3 and C-4 above. The Equation C-5 default value is based on information observed with respect to components (parapet and appendages) and equipment located on top of buildings and subjected to major earthquake ground motions (NCEER, 1993). In general, buildings will perform inelastically during major earthquakes, thereby reducing resonance amplification effects. It is not anticipated that powerhouse substructures will perform inelastically, so the default seismic force expressed by Equations C-5 is not likely to be appropriate for powerhouse superstructures and equipment. However, it should be recognized that amplification effects predicted using the information described in Sections C-3 and C-4 would be upper-bound values. Before any remediation is undertaken based on the proposed upper-bound values, a time-history analysis, as described below, should be performed.

C-6. Estimating the Period of the Substructure and Superstructure.

a. To apply the amplification effects as proposed in Sections C-3 and C-4 in a superstructure-only evaluation, the evaluator must be able to estimate the period of the superstructure and substructure with reasonable accuracy. Methods for estimating the period of the superstructure for the simple linear static procedure (LSP) and the regular LSP analyses are contained in Appendix B. When linear dynamic procedures (LDP) analysis is used, periods of vibration for the superstructure will be part of the response spectrum analysis output. Procedures for estimating the period of vibration of the substructure were developed using information contained in Ebeling, Perez-Marcial, and Yule (2006) and presented in Section C-2.

b. Based on information obtained from Ebeling, Perez-Marcial, and Yule (2006) and the period formulation approach used for dams by Fenves and Chopra (1985), the fundamental period of vibration for generator bay and erection/service bay block substructure models in the dry condition is approximately equal to:

$$T_1 = 1.5 \frac{H_s}{\sqrt{E_s}} \quad (C-6)$$

where:

T_1 = fundamental period of substructure (seconds)

H_s = height of substructure (ft)

E_s = modulus of elasticity of substructure (psi).

c. For the wet condition, the forebay and tailrace pool conditions are those assumed in Ebeling, Perez-Marcial, and Yule (2006). The forebay pool is assumed to be 20 ft above the top of the idealized substructure, and the tailrace pool 34.4 ft below the top of the idealized substructure. The height of the idealized substructure (H_s) and the idealized pool conditions are illustrated in Figure C-10 for the generator bay analytical model.

d. The fundamental period of vibration for the erection/service bay substructure in the wet condition is approximately equal to:

$$T_1 = 2.0 \frac{H_s}{\sqrt{E_s}}. \quad (C-7)$$

e. The fundamental period of vibration for the generator bay substructure in the wet condition is approximately equal to:

$$T_1^1 = 2.15 \frac{H_s}{\sqrt{E_s}}. \quad (C-8)$$

where T_1 is the fundamental period of the wet substructure (seconds).

f. The period formulations presented above (Equations C-6 through C-8) are a best fit to fundamental period data extracted from Ebeling, Perez-Marcial, and Yule (2006). Plots of the extracted data with the appropriate best-fit formulations are presented in Figures C-3 through C-6.

31 Oct 06

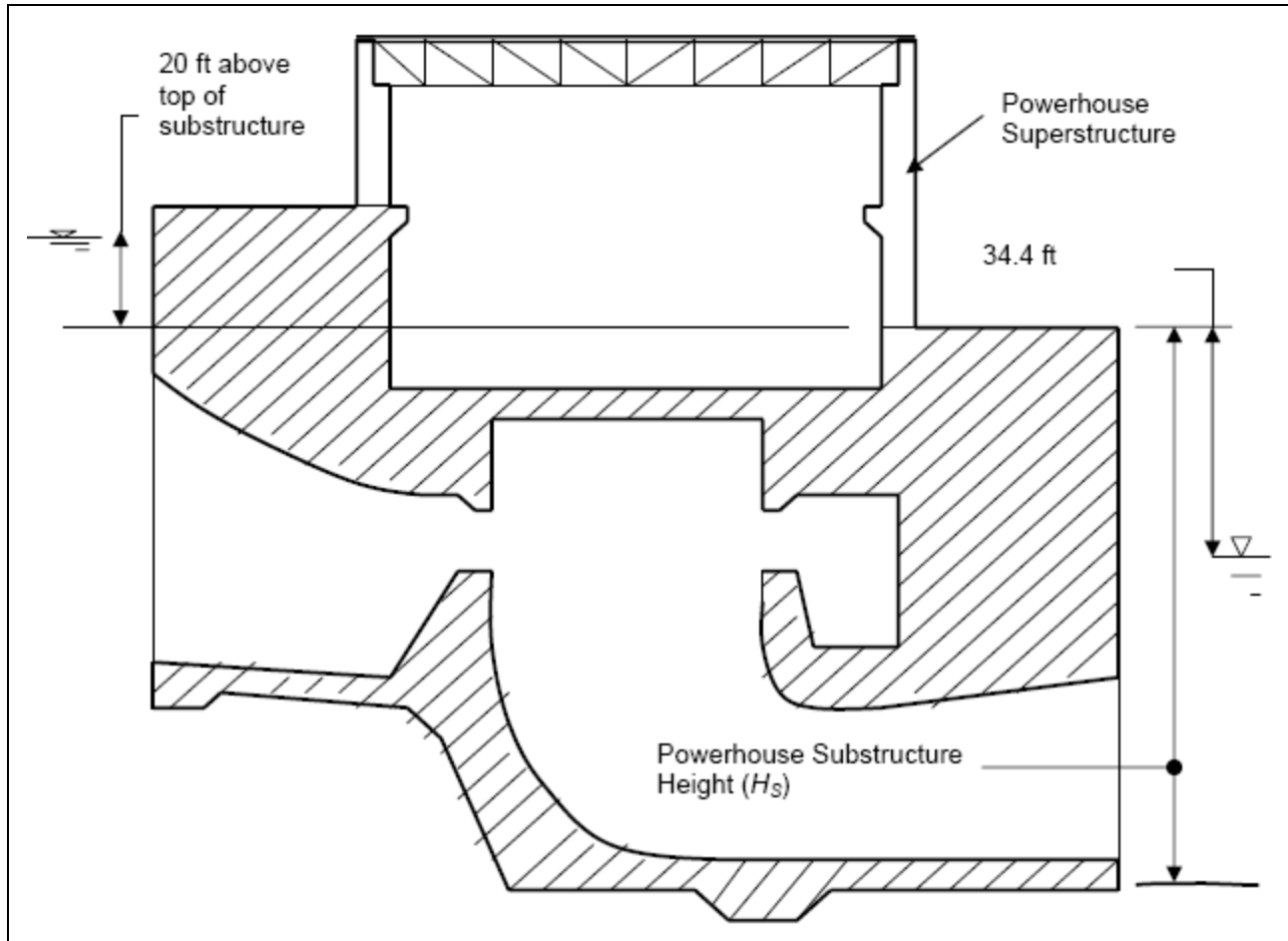


Figure C-10. Generator bay sectional elevation, with the forebay and tailrace levels representing “wet.”

g. For an erection/service bay substructure that is 100 ft high ($H_s = 100$ ft) and that has a modulus of elasticity equal to 3.7×10^6 psi ($E_s = 3.7 \times 10^6$ psi), the fundamental period (T_1) for the dry condition is:

$$T_1 = 1.5 \frac{H_s}{\sqrt{E_s}} = 1.5 \frac{100}{\sqrt{3700000}} = 0.078 \text{ seconds.}$$

h. For the wet condition with water 20 ft higher than the top of the substructure, the fundamental period (T_1^I) for the wet condition is:

$$T_1^I = 2.0 \frac{H_s}{\sqrt{E_s}} = 2.0 \frac{100}{\sqrt{3700000}} = 0.104 \text{ seconds.}$$

C-7. Estimating Superstructure Amplification Effects.

a. The ratio of the periods of the superstructure to substructure (T/T_I) can be determined using the formulations presented above for determining the period of the substructure and using methods described in Appendix B for determining the period of the superstructure. Knowing T/T_I and using the information provided in Figure C-4, the resonance amplification (a_p) can be determined. The resonance amplification per Figure C-9 is presented in Table C-9.

Table C-9. Period ratio (T/T_I) vs. resonance amplification (a_p).

Period ratio (T/T_I)	Resonance amplification (a_p)
$T/T_I \leq 0.5$	1.0
$0.5 \leq T/T_I \leq 0.7$	$20.00 (T/T_I) - 9.00$
$0.7 \leq T/T_I \leq 1.4$	5.0
$1.4 \leq T/T_I \leq 2.0$	$14.34 - 6.67 (T/T_I)$
$T/T_I \geq 2.0$	1.0

b. The resonance amplification values determined from Table C-9 must be multiplied by 1.2 to account for height-wise amplification (a_x) effects. Resonance amplification effects can be neglected when the period of the superstructure is more than twice that of the substructure ($T/T_I > 2.0$). Height-wise amplification effects can be neglected when the period of the superstructure is more than three times that of the substructure ($T/T_I > 3.0$). Resonance amplification effects can also be neglected when the period of the superstructure is less than half that of the substructure ($T/T_I < 0.5$), although it is extremely unlikely that the period of the superstructure will be less than that of the substructure.

c. The demands on superstructure-only models obtained from linear static procedure (LSP) or a linear dynamic procedure (LDP) analyses should be amplified when required and as suggested in the above discussion. Amplification effects are automatically included in the LDP analysis results when composite models are used. The demands from composite models, however, should be compared with amplified demands from the superstructure-only model. This comparison is necessary to make sure that peak response broadening as illustrated in Figure C-9 will not produce superstructure-only demands that are higher than those of the composite model. If this happens, the demands of the superstructure-only model should be used as the basis for demand-to-capacity ratio (DCR) evaluations.

d. The above comparison should also be made between superstructure-only analyses performed with standard top-of-rock spectra and performed with top-of-substructure spectra obtained from Ebeling, Perez-Marcial, and Yule (2006).

e. It is important that evaluators, when using composite analyses or top-of-substructure response spectrum analyses, consider only the low-frequency modes (fundamental mode for LSP analyses, Figure B-4 modes for LDP analyses) of the superstructure when performing demand-to-capacity ratio (DCR) evaluations for displacement-controlled actions (i.e., flexure). This is

because a displacement ductility demand value calculated based on moment demand (rather than displacement demand) per the FEMA 356 (2000) methodology will produce an unreasonably high displacement ductility demand and DCR.

C-8. Amplification by Time-History Analysis. Amplification effects obtained by amplified superstructure-only model LSP or LDP analysis or by composite model LDP analysis are considered to represent upper-bound demand conditions. If these upper-bound demands result in performance that is unacceptable, a linear elastic time-history analysis using demands from representative natural time-history records should be considered. With the time-history analysis, the peak demands can be examined with respect to the number and extent of the peak excursions critical to performance. Using the FEMA 356 (2000) performance-based evaluation techniques, it is assumed for reinforced concrete that strength and deformation capacities are for earthquake loadings involving three fully reversed deformation cycles to design deformation levels. Short-period structures (i.e., powerhouse superstructures) can be expected to sustain additional cycles to design deformation levels. Therefore, it is considered acceptable for evaluators to base the peak (amplified) time-history response on the average of the three cycles exhibiting the greatest demand.